Inter-comparison on multi-feature bar calibration for determining machine-tool geometric errors

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Abstract

To improve the accuracy of manufactured mechanical parts, the geometric errors of a machine-tool should be evaluated and compensated in order to better master the deviations between the actual and nominal tool positioning (volumetric accuracy). Thus, a novel Multi-Feature Bar (MFB) for machine-tool geometric errors' identification was designed and manufactured. The MFB standard is made of Invar material. The proposed design of the MFB allows extracting three intrinsic parameters: one linear positioning and two straightness errors. The calibration of the MFB was performed on an accurate coordinate measuring machine (CMM) when applying the reversal technique, in order to separate the MFB's error forms from the motion errors of the CMM's mechanical guiding systems. Furthermore, an intercomparison was conducted between four National Metrology Institutes (LNE, PTB, CMI, UM) to evaluate the reliability of the proposed calibration methodology. Findings resulting from this intercomparison reveal dimensional stability of the MFB standard for geometric errors identification on CMM and machine-tool. Therefore, the use on machine-tool of the calibrated MFB, regardless of the harsh environment, guarantees its metrology traceability to the SI metre definition of few micrometres (<5 µm).

1   Introduction

During the manufacturing process, the inspection of produced parts directly in the machine-tool(s) represents a more and more frequent need in the industry. The manufacture and measurement of these parts are usually performed through

high precision machine tools (MT) which must be in line with to the SI metre definition published by the Bureau International des Poids et Mesures (BIPM).

The volumetric error in quasi-static conditions is defined in ISO 230-1:2012 [1] as a relative deviation between actual and ideal tool and workpiece positioning on machine-tool. This deviation is essentially generated by geometric errors [2] (position and orientation errors and motion errors [1] [3]). Several other sources of the volumetric error such as thermal errors and loads can be identified by measuring the error motions [4].

Therefore the traceability and minimisation of the volumetric error on MT represent new challenges for researchers of National Metrology Institutes (NMIs) of manufacturing laboratories and/or plants. In this context, NMIs develop and deliver standards and procedures suitable to assess and ensure the traceability of the measurement capability of in-process metrology.

More particularly, this task consists in designing and manufacturing highly accurate multi-purpose material standards, which are robust against environmental influences and high mechanical stress, for the mapping of volumetric and task-specific measurement errors. The Laboratoire National de Métrologie et d'Essais (LNE, French NMI) has designed and manufactured a novel Multi-Feature Bar (MFB), depicted in Figure 1.

Figure 1: Multi-Feature Bar.

The new design of the MFB machined in Invar due to its small α/λ ratio equal to $7.7\ 10^{-8}$ m/W and specific technical attributes enables the identification of geometric errors on machine-tool in a harsh environment [5].

MFB consists of a repetition of a 3Dpattern in the Δ direction. Each pattern contains 7 features: 4 flat surfaces (vertical planes) and 3 cylinders (one vertical inner cylinder and two horizontal outer cylinders). The 3D pattern is displayed in Figure 2. Many measurements are carried out on each pattern. The processing of the measured data (48 probed points) allows extracting one point of interest Oi corresponding to the intersection of the 7 features previously mentioned. The expected measurements and the post-processing of the measured data (a total of 316 probed points) can be completed according to the steps detailed in [5].
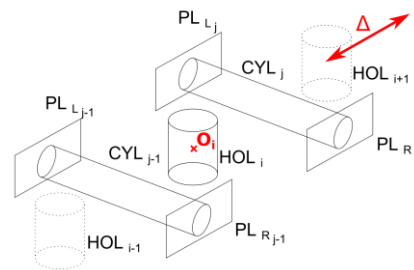
Figure 2: 3D pattern of the MFB.

The steps are repeated as many times as necessary to cover the whole geometry of the MFB. Thus, the identified points of interest $O_i = (x_i, y_i, z_i)$ offer 3 intrinsic geometric parameters in the local frame of the R_{MFB}: 1 linear positioning and 2 straightness errors contrary to the commercially available hole bar. R_{MFB} is built using the measured data on the surfaces of the patterns [5].

To ensure the traceability of measurement on machine-tool to the SI metre definition, the calibration of the MFB is carried out using an accurate CMM. In addition, the calibration is repeated 5 times in order to characterise its repeatability in a repeatability condition of measurement specified by the International Vocabulary of Metrology (VIM) [6]. In other words, the calibration was performed in a condition of measurement, out of a set of conditions that includes the same measurement procedure, same operator, same measuring system, same operating conditions and same location, and replicate measurements of the same or similar objects over a short period of time.

Furthermore, the specified reproducibility condition of measurement in the VIM is a condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

Therefore, despite a clearly specified calibration protocol, it is necessary to evaluate the reliability of the proposed calibration methodology by an intercomparison.

Agreements enable the NMIs to demonstrate the international equivalence of their measurement standards and their measurement certificates. These agreements are governed by the Mutual Recognition Arrangement (MRA) of the Comité International des Poids et Mesures (CIPM) (CIPM MRA). The CIPM MRA [7] ensures the international recognition of the Calibration and Measurement Capabilities (CMC) of participating laboratories. CMCs, once approved, are published in the CIPM MRA database, which also contains other technical information. This approval is objectively established on the basis of mutual recognition criteria. Approval is based on implemented means such as:

- international comparisons of measurements, referred to as Key Comparisons;
- international comparisons of additional measurements;
- the establishment by LNMs of quality systems and demonstrations of their skills.

In this context of CMC, a European intercomparison of the MFB was conducted by LNE.

This paper aims at comparing the calibration results of different NMIs to evaluate the reliability of the proposed calibration methodology.

The paper is structured as follows: Section 2 presents the summary of the calibration procedure of the MFB; Section 3 deals with the European intercomparison and the description of the reproducibility condition; Section 4 is dedicated to the NMIs' results and comparisons in relation to reference values.

2   Calibration Procedure

First of all, the MFB is assembled on the work holder. This task aims at maintaining the MFB during the measurement and providing an isostatic setting-up of the MFB. The calibration must be performed along any axis of CMM, but preferably along the axis presenting the smallest linear positioning error (i.e. E_{xx}, E_{yy}, E_{zz} or xtx, yty, ztz). The achievement of the assembly as displayed in Figure 1 is imperative to perform the calibration in similar conditions as those in the machine tools.

During the tightening, it is necessary to make sure that the washer is in contact with the spheres (isostatic link) and the mounting flange. The washer does not move after tightening. The tightening torque applied to the four nuts must be equal to 1.5 Nm. The nuts should be gradually embedded (Figure 3).
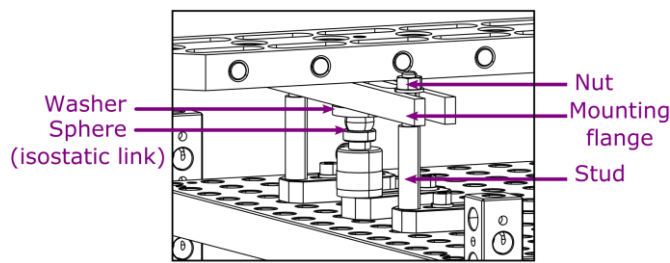

Figure 3: Fixture equipment of MFB.

Once the assembly is completed, the MFB is put into place on the CMM for the calibration. For the calibration of the MFB, the reversal technique is applied in order to separate the motion errors of the used accurate CMM from the straightness errors of the MFB. The absolute length between each hole can be corrected by a substitution technique. The motion errors of CMM contain both systematic component and random component. The application of the reversal technique allows determining the systematic components. The random component is still mixed with the geometric errors of the MFB; this is the reason why the measurements are repeated at least 5 times to average out the zero mean random errors.

For the application of the reversal technique, the MFB is carefully aligned along the CMM axis with the smallest linear positioning error that was previously

identified. The sine error due to the alignment defect along the entire length of MFB must be inferior to 0.1 mm. The calibration technique and expression of the linear positioning and straightness errors of the points of interest O_i are specified in [5]. For the calibration of the MFB, the following instructions should be observed:

- The MFB should be aligned along the selected axis with the smallest linear positioning error,
- The calibration of the selected axis should be performed previously by any other internal standard,
- The MFB should be aligned along the selected CMM,
- The measurement should be carried out by using a stylus with a diameter of 6 mm and a maximum length of 50 mm,
- The selected feedrate of motion during the deflection of the stylus shall not exceed 8 mm/s.

Each operator was provided with the instructions for the calibration process and the probing programmes. In any case, the operator has to repeat the measurement five times. The total number of measurements is equal to ten measurements (including five direct measurements and five reversal measurements). The calibration procedure is based on the schema displayed in Figure 4 where A, B and C are external flat surfaces of the MFB.

3   European intercomparison

An intercomparison of measurements is performed on the LNE Material Standard: the MFB. This intercomparison between several organisations (as seen in Table 1 and Figure 5) ensures that the measurements of the MFB all produce results that are within an acceptable tolerance. The measurements are performed by four NMIs across Europe: LNE, PTB, CMI, UM. The reproducibility condition is then respected: different locations, operators, measuring systems, and replicate measurements of the same or similar objects (in this case the MFB) with the same measurement procedures.

The MFB and all the elements necessary for the fixation, such as the plate, the modular inspection equipment system, the screws and the torque wrench are inserted in the individual Transport Case.

Therefore, the NMIs perform measurements for the calibration of the MFB with the same equipment, except the CMM.
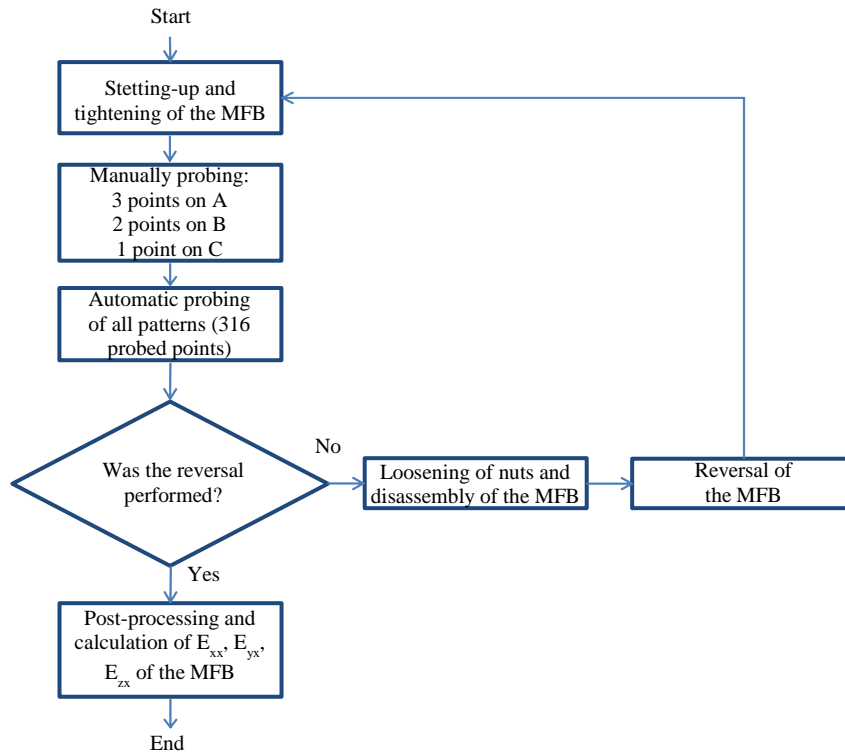
Figure 4: Calibration procedure of the MFB.

Table 1: List of the institutes involved in the intercomparison and the various CMMs, with their associated MPEs, temperature during measurements and CMM axis where the MFB is aligned.

	CMM	Workspace size (m × m × m)	MPE / µm (L in mm)	T (°C)	CMM axis
LNE	Renault Automotion 251310	2.5 × 1.3 × 1	4,5 + L × 4,0	20,26 ± 0,03	Z
CMI	SIP CMM5	0.7 × 0.7 × 0.55	0,8 + L × 1,3	19,73 ± 0,09	X
UM	Zeiss UMC 850	1.2 × 0.85 × 0.6	2,1 + L × 3,3	20,39 ± 0,03	Z
PTB	Zeiss UPMC 850 CARAT	0.85 × 1.2 × 0.6	0,8 + L × 3,5	20,18 ± 0,04	X
LNE	Renault Automotion 251310	2.5 × 1.3 × 1	4,5 + L × 4,0	20,04 ± 0,03	Z

Measurements of the MFB are performed by the above-mentioned institutes and the results collected by LNE. The positions of the points of interest O_i are extracted according to the procedure defined in [5]. The extraction allows quantifying the three intrinsic geometric errors of the MFB: one linear positioning error ($E_{xx\ MFB}$) and both straightness errors ($E_{yx\ MFB}$, and $E_{zx\ MFB}$). The straightness errors are defined on end-point reference straight line.

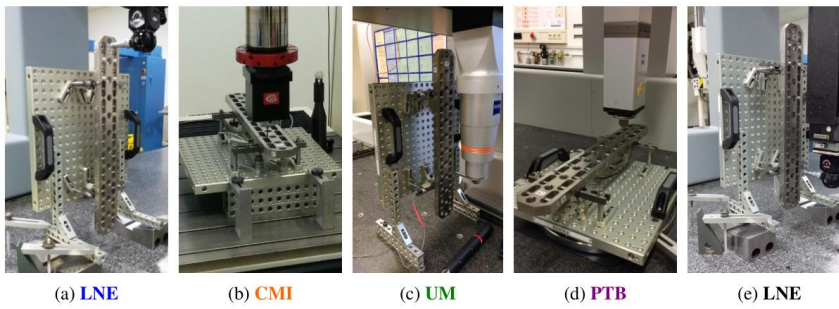(a) **LNE**   (b) **CMI**   (c) **UM**   (d) **PTB**   (e) **LNE**

Figure 5: LNE material standard during measurement in the institutes.

4   Results and reference values

The extraction of the points of interest is performed by LNE from the probed points in the institutes by using the CMMs. The results of identified errors $E_{xx\ MFB}$, $E_{yx\ MFB}$, and $E_{zx\ MFB}$ are shown respectively in Figure 6, Figure 7 and Figure 8. The uncertainty depicted in Figure 6, Figure 7 and Figure 8, is the repeatability of measurement. Deviations between the results of participants especially for Exx HB (Figure 6), and Ezx HB (Figure 8) may be noticed.. In order to identify the cause of this deviation, various factors were investigated and are discussed below.

4.1   Impact of the MFB's weight and orientation

The MFB is fixed on a specific holder, built with modular inspection equipment systems, via isostatic assembly composed of 3 mechanical linkages (spherical joint, point surface joint and point curve joint). This type of assembly avoids any transmission of the mechanical and thermal deformation of the holder to the MFB. Three mechanical linkages are located on the points of minimum deflection that were analytically calculated (0.16 µm without tightening operations) [5]. This value is compensated by reversal technique during the calibration of the MFB. Therefore, the impact of deflection is not the reason that could explain the difference between Ezx HB results. It can be concluded from Figure 8 and Table 1 that the MFB was deformed during intercomparison, and particularly between the first measurements by LNE and CMI.

Moreover, modular inspection equipment system enables the orientation and location of the MFB along any direction in the MT workspace (Figure 5). The change in length of the MFB when standing vertically, due to its own weight, is equal to 52 nm and is neglected with respect to the magnitude of the identified errors [5].
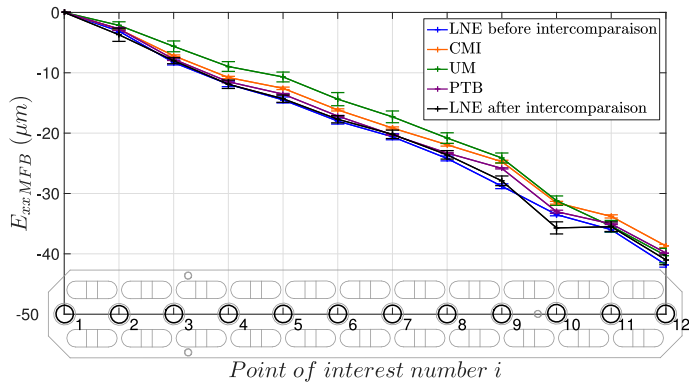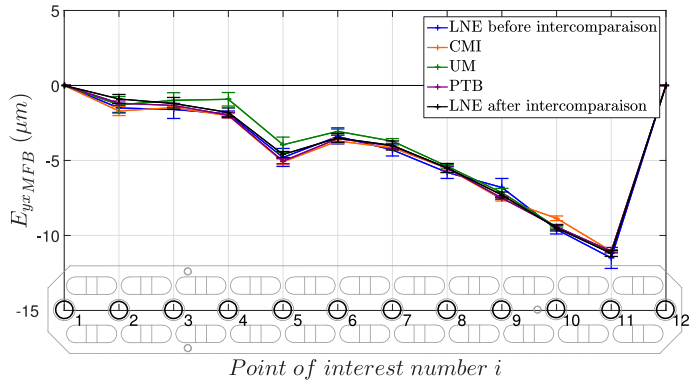
Figure 6: Linear positioning error E$_{xx\ MFB}$.

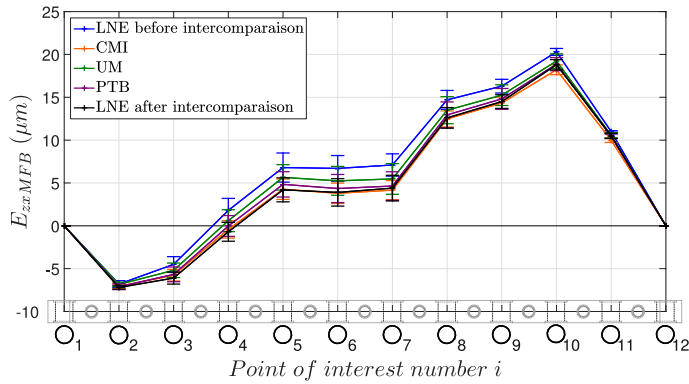Figure 7: Horizontal straightness error E$_{yx\ MFB}$.

Figure 8: Vertical straightness error Ezx $_{MFB}$.

4.2   Impact of the tightening operation

The tightening operation generates a deviation equal to -4.7 µm on the deflection of the MFB coupled with a deviation on its length (-3.7 µm) with the variability of 2,7 µm identified by deflection and length measurement for 50

cycles of tightening and loosening. Despite careful attention and design of the clamping system, the latter introduces random errors during the calibration process. The use of a clamping system reducing all deformations due to tightening could be investigated in the future (e.g. using isostatic decoupling link).

4.3   Reference values

The reference values were calculated by using all the measurements. Indeed, the five measurements of each participant are used to calculate a mean value, named reference value of the identified errors $E_{xx\,MFB}$, $E_{yx\,MFB}$, and $E_{zx\,MFB}$. The results are presented in Table 2.

Table 2: Reference values of the MFB

O_i	$E_{xx\,MFB}$ mean (µm)	u (µm)	$E_{yx\,MFB}$ mean (µm)	u (µm)	$E_{zx\,MFB}$ mean (µm)	u (µm)
1	0	0	0	0	0	0
2	-3,0	0,8	-1,3	0,4	-7,1	0,3
3	-7,5	0,9	-1,3	0,4	-5,5	0,9
4	-11,2	1,1	-1,8	0,4	-0,1	1,4
5	-13,3	1,3	-4,4	0,5	5,0	1,6
6	-16,9	1,3	-3,5	-0,3	4,7	1,7
7	-19,7	1,2	-4,1	0,3	5,0	1,7
8	-22,9	1,2	-5,5	0,3	13,1	1,4
9	-26,4	1,8	-7,3	0,4	14,9	1,1
10	-33,2	1,8	-9,3	0,3	19,0	0,9
11	-35,1	0,9	-11,2	0,3	10,5	0,4
12	-40,3	1,2	0	0	0	0

The deviations between the reference values of $E_{xx\,MFB}$, $E_{yx\,MFB}$, and $E_{zx\,MFB}$, and the identified values of $E_{xx\,MFB}$, $E_{yx\,MFB}$, and $E_{zx\,MFB}$ for each participant are shown in Figure 9, Figure 10, and Figure 11. The Figure 11 depicts a variation of the geometry during the intercomparison between LNE and CMI.

5   Conclusions

This paper describes an intercomparison of the novel Multi-Feature Bar (MFB) calibration. The progress of this innovative geometry that ensures the identification of three parameters has been tested by NMIs and provides a high level of confidence regarding the calibration. Despite reference values with small associated standard uncertainties of reproducibility, improvements and studies aiming at an easier and faster calibration will be carried out on the basis of the feedback provided by NMIs. Further works will be conducted by the application of procedures from this specific set of key comparison data to provide a key comparison reference value (KCRV) and the associated uncertainty [8].
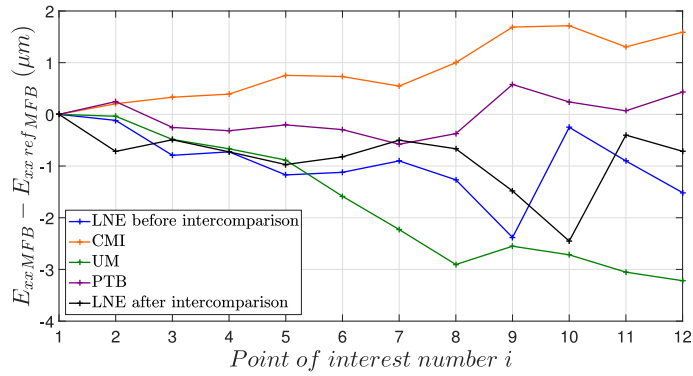
Acknowledgments

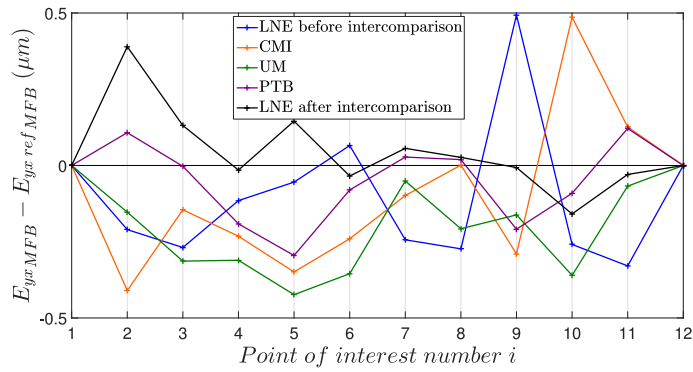Figure 9: Deviation between identified $E_{xx\ MFB}$ and the reference values.

Figure 10: Deviation between identified $E_{yx\ MFB}$ the reference values.
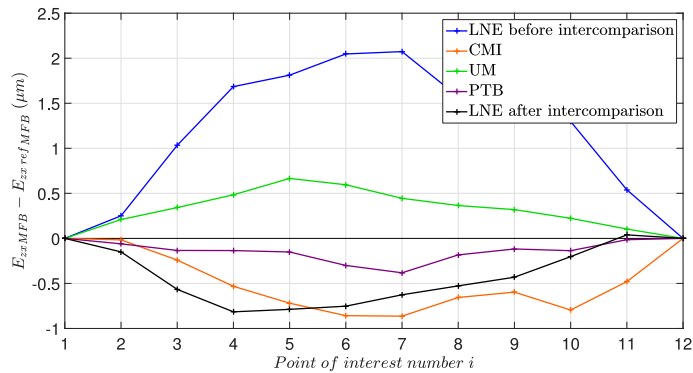

Figure 11: Deviation between $E_{zx\ MFB}$ and the reference values $_{MFB}$.

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